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AI-Assisted Robotic Prosthetics: Enhancing Mobility and Functionality

Kamanzi Ntakirutimana G.

School of Natural and Applied Sciences Kampala International University Uganda

ABSTRACT

AI-assisted robotic prosthetics have revolutionized the field of mobility restoration by offering advanced solutions for individuals with limb loss. These prosthetics integrate artificial intelligence (AI) technologies with mechanical components to mimic natural limb movement, enhancing functionality and adaptability. The paper examines the history, current technologies, and clinical applications of robotic prosthetics, focusing on the role of AI in user behavior prediction, control adaptability, and personalized prosthetic design. Key developments, including machine learning algorithms and sensor fusion techniques, have enabled more intuitive control and improved outcomes for users. However, challenges such as real-time processing, ethical concerns, and cost remain, and future advancements must address these for widespread adoption. This review highlights the potential of AI to transform the prosthetic industry, improve mobility, and enhance the quality of life for individuals with amputations.

Keywords: AI-assisted prosthetics, robotic prosthetics, machine learning, sensor fusion, neural control.

INTRODUCTION

AI-assisted robotic prosthetics aim to aid and restore lost mobility and functionality due to limb loss. Throughout the years, there have been state-of-the-art solutions in the form of prosthetic technology innovations. The multifunctional and mind-controlling features are some of the advantages of advanced upper-limb prosthetics. These advancements bring potential benefits to amputees, allowing them to act independently, restore natural human performance, and potentially avoid the formation of secondary disorders and complications. Currently, patients with limb loss can directly benefit from the integration of mechanical prosthetics with AI in practice. However, the individual management of patient limbs has never been discussed in this study, although individual conditions and residual limbs or limb functions differ. Furthermore, the combination of mechanical prosthetics with AI concepts has only been used for research purposes and will shift to practical applications. The AI and robotic prosthetic discussion focuses on aspects of individual control of the components integrated through neural prosthetics [1, 2]. While the development of robotic prosthetics may be subject to some criticism, there is little doubt that robotics, in general, contributes to the well-being of people and their quality of life. The aim is to aid individuals who are currently fitted with prosthetic limbs by integrating different components, such as EMG sensors, signals, and prosthetic limb controllers. This cutting-edge technology is not just focused on long-term technologies but is also expected to be incorporated into practical applications specifically, in clinical practice. We hope that noteworthy innovations created in the fields of robotics, AI, and upper-limb prosthetics will change and reform the lives of individuals suffering from amputations [3].

FUNDAMENTALS OF ROBOTIC PROSTHETICS

The study of robotic prostheses is fundamentally based on the kinematic and dynamic models that enable a prosthesis to emulate natural functionality. In this section, we briefly introduce the mechanics of the human body, including the musculoskeletal and neuromuscular models, and subsequently present the kinematic and dynamic models of the lower-limb prostheses to highlight the state-of-the-art solutions. The complexity added to the listed mechanical models by including an amputee's neuromuscular model will be addressed and developed in later sections after introducing the control strategies that govern the implementation of the robotic prostheses. Human Locomotion: The human body is an interconnected system built of bones and muscles that are voluntarily contracted or relaxed, effectively acting as interdependent forces and performing powerful movements. A neuromuscular control system regulates which muscles are contracted to perform the intended movement. This regulation occurs under the effect of sensory information that includes location, load, and velocity feedback of the concerned limb and proprioceptive signals, i.e., muscle and limb position, and muscle tension. This feedback is processed by tasks within the Central Nervous System, which include i) motor outflow to execute the movement, ii) sensory feedback integrating and processing to refine the movement parameters, iii) sensory feedback fusion across the limbs, and iv) sensory feedback sent to balance systems [4].

HISTORY AND EVOLUTION

The concept of artificial limbs dates back to ancient Egyptian times. The earliest found prosthetic limbs were those of a mummy known as Pepy. The prosthetic was constructed in 950 BC and was a simple toe replacement. This toe piece was an example of early successful designs of artificial limbs and is the first recorded example of a joint prosthetic. The toe was made of wood, which was secured to the foot as needed with a stitched leather attachment. The original stump was fitted with a small compartment of resin, which helped in cushioning and absorbing everyday impact during walking. The prosthesis is thought to have been created by healers looking to make a cripple walk once more instead of by a doctor or craftsman. Meanwhile, the prosthetic of the mummy of Greville Chester, which also would be dated to 600 BC, appears to be the same whether it was the original from his first life or a newer one owned afterward by his relatives. Nowadays, this progress can still be found in biomedical research [5, 6].

COMPONENTS AND TECHNOLOGIES

Prosthetics are often composed of an attachment, a suspension, and a foot. Attachment and suspension systems are usually customized to the prosthetic user for optimum function. In this text, we refer to a user wearing a prosthetic as an amputee. The level of amputation determines the kinds of prosthetic components available, how close the system can be to that of an unimpaired limb, and the degree of difficulty required for advanced motions. Aside from prostheses, orthoses seek to enhance the human function of a disadvantaged joint, such as the human knee or ankle and are used for stroke, spinal cord injury, and an array of joint diseases and disorders [7, 8]. A neural prosthesis can be developed to restore the function of a limb in a motor-imagery-based brain-machine interface. Neural prosthetics can leverage electrical signals measured with electromyography, accelerating the currently emerging field of direct neural control for the next generation of highly functional robotic prostheses. The term brain-machine interface describes where machinery such as computer systems can augment or connect to the human brain. Special consideration is given to visualization and multimodal data fusion, where biomechanical simulation and deep learning techniques can also be used to automate design [9].

INTEGRATION OF ARTIFICIAL INTELLIGENCE

The integration of technologies in artificial intelligence (AI) has significantly influenced the development of robotic prosthetics, whether it is lower or upper limb. AI-assisted prosthetics can either learn from the user's behavior and offer an output that would adapt to the user's expectations and therefore be more intuitive, or predict the user's intentions and enhance adaptability. AI algorithms that are applied in these robotic prosthetics include machine learning, particularly deep learning, and sensor fusion techniques, which combine information coming from various sources, such as cameras, inertial measurement units, or pressure sensors [10]. Three main AI technologies are utilized in robotic prosthetics: machine learning algorithms, sensor fusion techniques, and AI for sensory feedback. These technologies improve user behavior prediction, control adaptability, safety, and limb functionality. They also contribute to enhancing mobility, quality of life, and providing a natural feeling. This text explores the impact of AI on different aspects of robotic prosthesis development and applications, including requirement elicitation, user studies, control system development, phantom limb pain, and specialist applications. The review covers both lower and upper limb prosthetics and considers the user perspective. It also highlights the potential of AI in advancing this field [11].

MACHINE LEARNING ALGORITHMS

Machine learning algorithms power AI-assisted prosthetics, analyzing users' movements and adjusting the prosthetic's response. The cutting-edge algorithms used include supervisory learning, reinforcement learning, and deep learning. These algorithms require diverse joint movement data to improve accuracy and provide a more user-friendly experience. The learning process allows for adaptability and personalization of the prosthetic [12, 13]. A team trained a prosthetic hand with high accuracy using a support vector machine. Ground truth comparisons showed near-perfect motor intention recognition. Hardware was used to control the hand. Information integration design improved classification rates. An unsupervised SVM-assisted fuzzy classifier was developed. A neurofeedback system with spinal cord epidural stimulation is being developed [14].

SENSOR FUSION TECHNIQUES

Sensor fusion techniques combine different sensors to accurately control prosthetic movement. However, direct motor measurements can be limited and misleading due to joint friction and prosthetic components. Integrating sensors like accelerometers and gyroscopes allows for a more accurate understanding of user commands and environmental conditions. Precision and minimal errors are key in sensor fusion systems, but real-time signal processing and sensor placement pose challenges. Advanced algorithms, like adaptive network-based fuzzy inference systems, have improved performance in sensor fusion and prosthetic development [15, 16].

CLINICAL APPLICATIONS AND CASE STUDIES

Clinical Applications and Case Studies: There are a growing number of reports on the application of advanced algorithms and robotics to prosthetics, including examples of experiments specifically designed to evaluate the effectiveness of AI-assisted robotic prosthetics. Individual reports were particularly enlightening about the user and their situation and, in combination, represented a coherent body of evidence. In the process of adaptation to the user, a number of studies have developed data-driven prosthetic control techniques. This is also validated by insights from clinical observations. Adaptation capabilities were demonstrated by both bilateral and unilateral prosthesis users. Hence, this essentially forms a state-of-the-art analysis on AI-assisted prostheses in the context of clinical application [17]. We found common user experiences and insights from three case studies on AI prosthetics. User experiences should be integrated with commercially available AI prosthetics. The ability to accurately assess AI-assisted outcomes is useful. User-specific AI has potential based on clinical performance and co-development of algorithms. Optimization for customizable controllers is valuable. Future clinical research should consider real-life features and the value of AI. AI prosthetics should be more accessible for a wider range of studies. Interviews with individuals from various backgrounds were conducted using a standard open interview method. Healthcare professionals expressed interest in AI prosthetic control and the link between individual learning and outcomes. Clinical research and co-design are essential for improving outcomes. User outcomes must be captured in a practical setting [18].

CHALLENGES AND FUTURE DIRECTIONS

There are several technical, social, and ethical challenges facing the introduction of AI-assisted robotic prosthetics. One of the main concerns associated with the use of AI in robotic prosthetics is ensuring the robustness of the AI systems. AI systems that are used in automated assistive technologies should maintain high levels of accuracy in uncertain and varying conditions. In order to guarantee the reliability of such AI and, in turn, the safety of the prosthetic system, automated monitoring and on-board real-time analysis of the prosthetic system should be possible. This is particularly important considering the long-term nature of using such systems. Regular updates of AI systems and real-time modifications should accommodate the learning process of individuals with limb differences. In addition to technical challenges, there are social considerations that should be addressed when developing AI-assisted robotic prosthetics. Some individuals with limb differences may opt to use these assistive technologies, whereas others may prefer not to use them. It is not yet clear how this field can reach an industrially scalable solution that caters to different user preferences. However, it is recommended that the user be involved in the design and development of intelligent prostheses to enable easy customization [19, 20]. Ethical issues such as privacy and cost must be resolved for AI-assisted prosthetics. Customizable and cost-effective designs should be implemented. Integration of technology and ethical guidelines is crucial. Research should focus on user control and interdisciplinary collaboration. Technical advancements will improve daily actions and quality of life for users. Collaboration is necessary to fully realize the potential of AI and robotics in prosthetics [21].

CONCLUSION

AI-assisted robotic prosthetics are a huge step forward in enhancing mobility and restoring usefulness for people with limb loss. Using AI technologies, these devices have grown to provide more intuitive, adaptive, and personalised solutions. Machine learning algorithms, neural interfaces, and sensor fusion have all helped to improve user experience and control, making robotic prosthetics more efficient and effective. While challenges like as real-time adaptability, ethical constraints, and financial limitations persist, the future of artificial intelligence in prosthetics promises to improve clinical practice and daily living for amputees. Continued research and interdisciplinary collaboration are critical for addressing these challenges and providing accessible, sophisticated prosthetic solutions for everybody.

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